NLTE Calculations of a Na D Doublet in the Atmosphere of the Transiting Planet HD209458b

Travis S. Barman, Peter H. Hauschildt, Andreas Schweitzer, Phillip C. Stancil

Dept. of Physics and Astronomy & Center for Simulational Physics, University of Georgia, Athens, GA 30602-2451, USA

E. Baron

Dept. of Physics and Astronomy, University of Oklahoma, 440 W. Brooks, Rm 131, Norman, OK 73019-0260, USA

France Allard

C.R.A.L (UML 5574) Ecole Normale Superieure, 69364 Lyon Cedex 7, France

Abstract. The observation of sodium absorption in the atmosphere of HD209458b, the only EGP known to transit its parent star, is the first direct evidence of an EGP atmosphere. We explore the possibility that neutral sodium is *not* in local thermodynamic equilibrium (LTE) in the outer atmosphere of irradiated EGPs and that the sodium concentration may be underestimated by models that make the LTE assumption. Our results indicate that it may not be necessary to invoke excessive photoionization, low metallicity, or even high altitude clouds to explain the observations.

1. Introduction

The effects of non-local thermodynamic equilibrium (NLTE) offer a natural explanation for the apparently low sodium absorption observed in HD209458b (Charbonneau et al. 2002) without the need for excessive ionization, a reduced metallicity, or extremely high altitude clouds (see Barman et al. 2002). Below we present theoretical predictions for NLTE Na D doublet line profiles for the transmitted spectrum of an irradiated EGP atmosphere and provide stringent limits on the NLTE effects.

2. Model Construction

The construction of the model atmospheres presented below follows the procedure outlined by Barman, Hauschildt & Allard (2001). We model the flux transmitted through the limb of the planet's atmosphere by solving the spherically symmetric radiative transfer equation (SSRTE) modified to account for the incident radiation. The incident flux is taken from a separate calculation which

reproduces the observed spectrum of HD209458. When solving the SSRTE, the atmosphere is modeled as a discrete number of concentric shells surrounding the interior (or "core"). The solutions along characteristic rays that pass through the outer most shells are all that are needed to calculate the transmitted intensities and automatically account for the curvature of the limb.
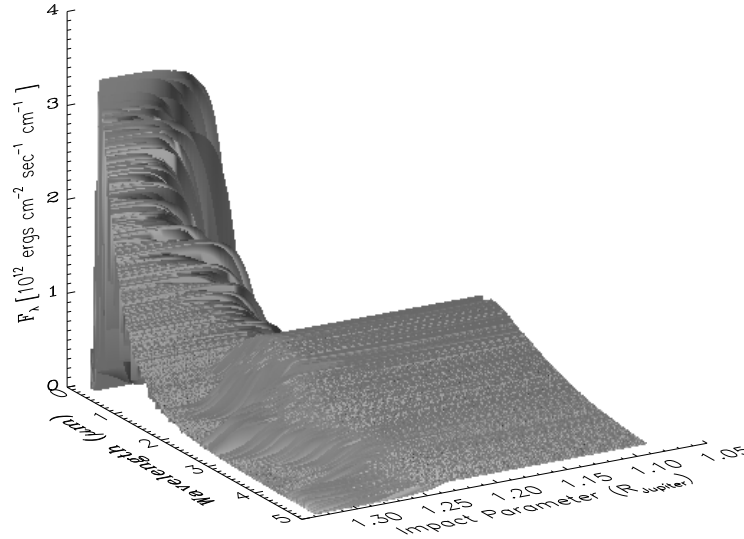

Figure 1.   The model fluxes (F_λ) at various center-to-limb distances (impact parameter).

We have produced several irradiated model atmospheres which allow the level populations of neutral sodium to depart from their LTE values. The first irradiated model (A) only includes collisions with electrons in the solution of the rate equations. Even in an irradiated EGP atmosphere, the number density of electrons is very small ($N_e/N_{H2} \sim 10^{-8}$), and the temperatures are too low for electronic collisions to be important. Model A, therefore, can be considered a lower limit for the collisional rates. The second irradiated model (B) has the same parameters as model A, except that collisions with H_2 are also included. In order to place a secure upper limit on the effects of collisions with H_2, we have treated H_2 as if it had the same rate coefficients as an electron, in which case we are overestimating the H_2 collisional rates by more than an order of magnitude.

3.   Results

An example of the model fluxes as a function of impact parameter (center-to-limb distance) is shown in figure 1, where one can see the simultaneous limb-*darkening* in the IR and limb-*brightening* in the optical. At small impact parameters, only the thermal IR spectrum of the planet is visible. At large impact parameters (close to the limb), the planet's atmosphere becomes optically thin and allows

stellar flux to be transmitted. At the outermost edge, only the stellar spectrum is visible.

The departures from LTE are demonstrated in figure 2 (left panel). The largest departures are seen in model A where the 3s (ground state) and 3p levels are both underpopulated by many orders of magnitude, especially in the limb region. The main reason for such large departures is that only collisions with electrons were included and, in such a cool atmosphere, the number density of electrons is ~ 8 orders of magnitude below that of the dominant species, H_2. Consequently, there are essentially no collisions in model A to thermalize the level populations in the Na atom, thus allowing the radiative rates to dominate and drive the system out of LTE.

The effects on the Na D line profiles for model A are shown in figure 2 (right panel). In model A, the lack of thermalization reduces the line transfer to nearly a pure scattering case. As a result, the doublet appears completely in emission. However, in model B, as the collisional rates are increased, the line wings return to their LTE shape while the line cores are reversed. The Na absorption in model B would result in a transit deeper than in the continuum bands but not as deep as implied by the LTE model. The fact that Na D absorption (and not emission) has been observed in the transmitted spectrum of HD209458b rules out our model A, indicating that some thermalization does occur in the limb region. However, it is unlikely that the collisional rates are as large as those in our model B, suggesting that the equivalent width of the Na D doublet will be substantially reduced by NLTE effects.

The reduced equivalent width predicted by our model is *not* due to photoionization of Na. In the majority of the limb, only 3% is ionized and the neutral Na concentration is nearly constant with $N_{Na}/N_{H2} \sim 10^{-5.5}$. Na is only significantly ionized ($\gg 5\%$) at the very top of the atmosphere where $P_{gas} < 1$ μbar. The shallow ionization depth of Na is due to the strong UV opacity provided by metals (e.g. atomic Mg, Al, Ca, Fe, and Ni) which effectively shield Na from the incident ionizing photons. The ionization predicted by our models (even 3%) is far greater than what is obtained from an LTE calculation but does not significantly affect the line profile. However, if the planet's atmosphere is substantially cooler than in our model, then additional condensation and settling could further deplete the atmosphere of metals and allow greater ionization of Na to occur.

4.   Conclusions

Our models clearly show that Na is far from being in LTE in the upper atmosphere of HD209458b and the observed Na absorption can be explained with a solar metallicity atmosphere which is cloud free or has only very low lying clouds. Other important species (e.g. CO and CH_4) are likely in NLTE, and we plan to test the LTE assumption for a wide variety of atomic and molecular species in a future work. Hopefully the Na D doublets and other alkali metal lines will be useful diagnostics in the study of EGP atmospheres. However, only with detailed NLTE calculations, including well-determined collisional rates, will we have a chance at constraining the physical conditions in the atmosphere of HD209458b.
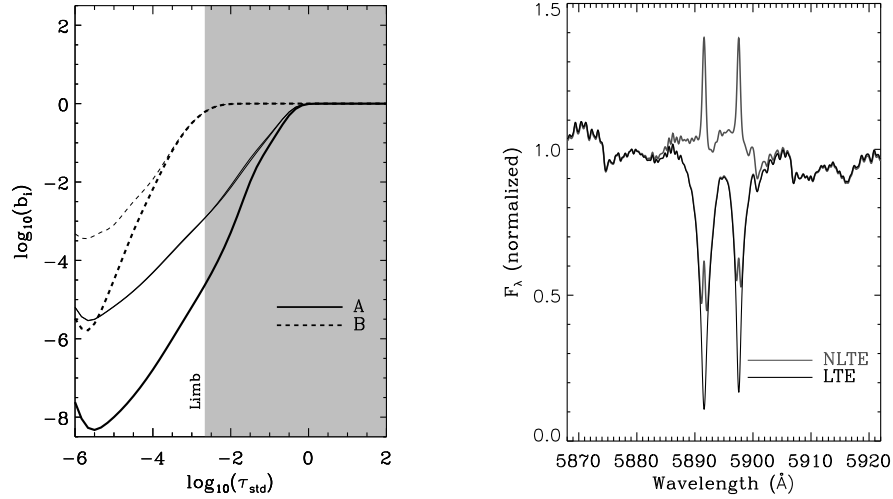
Figure 2.   Left: the departure coefficients for neutral sodium in the atmosphere of HD209458b as a function of the radial optical depth at 1.2 μm (τ_{std}). $b_i = n_i^\star/n_i$, where $n_i^\star$ is the NLTE population density for level i and n_i is the LTE value (Mihalas 1970). Thick lines refer to the 3s level (ground state) and thin lines indicate the 3p levels (for $J = 1/2$ and $J = 3/2$). See text for more details. Right: the Na D doublet for Model A (top gray line), Model B (lowest gray line), and when assuming LTE (solid line). The flux has been normalized to one at 5880Å.

References

Barman, T. S., Hauschildt, P. H., Schweitzer, A., Stancil, C., Baron, E. & Allard, F. 2002, ApJ, 569, L54

Barman, T. S., Hauschildt, P. H., & Allard, F. 2001, ApJ, 556, 885

Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377

Mihalas, D. 1970, Stellar Atmospheres (1st ed.; New York; Freeman)